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SHORT COMMUNICATION

Factors affecting relative humidity during wood vacuum drying

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Abstract: Effects of pressure and temperature in the chamber during vacuum drying on the relative humidity and evaporation of wood surface were investigated by using the vacuum chamber. The setting temperature during vacuum drying included dry-bulb temperature t_d, the wet-bulb temperature t_w and the temperature difference between the air in the vacuum chamber and the cooling water in the condenser. Results indicated that relative humidity during vacuum drying was affected by the dry-bulb temperature t_d, the wet-bulb temperature t_w and the temperature difference between the air in the vacuum chamber and the water in the condenser. Relative humidity of wood decreased with the increase in temperature at the given temperature of the water in the condenser. The relative humidity was affected slightly by pressure in the vacuum chamber p_A, and it decreased from 70% to 65% with p_A increased from 50 kPa to 101 kPa. Moreover, there was nearly no evaporation under the vacuum without external heating.

Keywords: influencing factors; radio frequency; relative humidity; wood vacuum drying

Introduction

Water transfer in wood is an important problem in wood drying. Relative humidity is one of the most important factors affecting the water transfer in wood. Therefore, detection of relative humidity during wood drying and analysis of related influential factors have great significance to determining the mechanisms of moisture transfer that is known to occur along a pressure gradient during vacuum drying (Koumoutsakos et al. 2001; Chen 1997, 2004; Li et al. 2006). During radio frequency/vacuum (RF/V) drying, a large amount of moisture is transferred longitudinally in form of vapor along a pressure gradient in a upper vacuum, while under a lower vacuum the proportion of diffusion in water transfer increases and the influence of pressure gradient on drying rate decreases (Cai and Hayashik 2001; 2002; 2003). Few studies have examined the phenomenon of surface evaporation and the factors affecting relative humidity during wood vacuum drying. In the process of vacuum drying, water at the wood surface boils before water inside the wood, and the boiling layer moves from the surface to the center (Chen 2001). Theoretically, water in a well-sealed vacuum chamber vaporizes at a higher temperature higher than the boiling point during the vacuuming process except in the very short time of starting vacuuming which water vaporizes in the form of surface evaporation, because the vapor pressure is equal to the pressure in the chamber (Siau 1995; Shin 1998). In reality, due to leakage, there is some mixing of dry air and water vapor in the vacuum chamber. As temperature increases through radiation and conduction, the relative humidity in the chamber drops and moisture evaporates from the wood surface. In this study, the phenomenon of evaporation from the wood surface during vacuum drying was examined, and factors affecting relative humidity were also analyzed.

Materials and methods

A container filled with water was placed into the vacuum chamber and the chamber was heated by using a heater strip (Fig. 1). The dry-bulb temperature t_d was maintained around 37°C, and the pressure was controlled at between 50 kPa and 101 kPa. The dry-bulb temperature t_d and the wet-bulb temperature t_w were measured by using a platinum resistance temperature sensor.

Samples of Japanese cedar (12 cm × 12 cm × 50 cm) containing heart wood were placed into the RF/V chamber (Fig. 2), and dried under the following conditions. The wood-center temperature Tc was maintained at 70°C, and the pressure difference ΔP between the chamber's pressure and the saturated vapor pressure (at the given Tc) was 6.7 kPa. The dry-bulb temperature t_d and the wet-bulb temperature t_w were measured in the chamber during RF/V drying.

The relative humidity φ in chamber was calculated as follows (The Japan Society of Mechanical Engineers 1959).

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$$\phi = \frac{p_w - k\frac{p}{755}(t_d - t_w)}{p_s} \times 100(\%) \quad (1)$$

where t_d is the dry-bulb temperature, t_w the wet-bulb temperature, p_s the saturated vapor pressure at the given t_d, p_w the saturated vapor pressure at the given t_w, and p the pressure of wet air (i.e. pressure p_A in the vacuum chamber). The value of the coefficient k is 0.5 when air flows, but there is little air in the vacuum chamber, thus k is equal to 0.6.

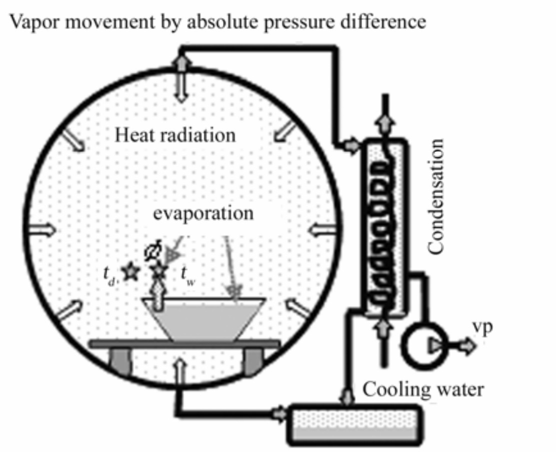

Fig. 1 Measure of relative humidity in the vacuum chamber during chamber body heating

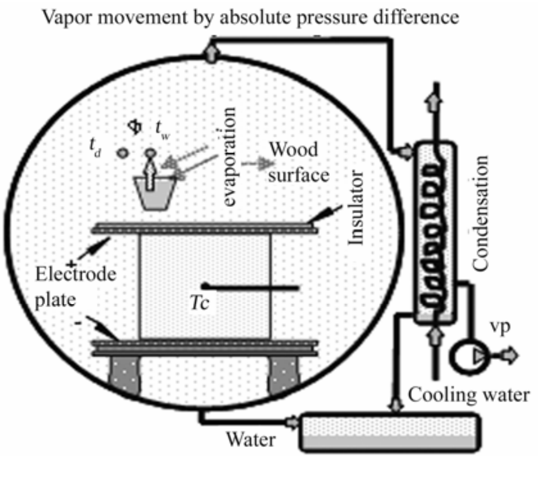

Fig. 2 Measure of relative humidity in the vacuum chamber during radio frequency/vacuum drying

Japanese cedar (*Cryptomeria japonica*) and Douglas fir (*Pseudotsuga menziesii*) were used to make specimens of 12 cm × 12 cm × 35 cm and 9 cm × 9 cm × 22 cm, respectively. The specimens were placed into the vacuum chamber and dried by using the chamber-heating method (Fig. 3). The dry-bulb temperature t_d was maintained at about 35°C for 96 h, then keeping heating stopped from 97 h to 192 h. The pressure in the vacuum chamber was reduced to 7.5 kPa and maintained at that pressure for 24 h. The pressure increased to 13.6 kPa, and then was maintained at 8 kPa to 120 h and then at 6.7 kPa from 121 h to 144 h and finally at 9.3 kPa from 145 h to 192 h. The dry-bulb and wet-bulb temperature was measured, and the relative humidity in the vacuum chamber was calculated by using the Equation 1.

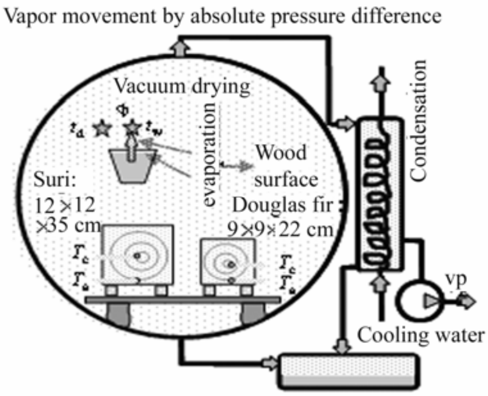

Fig. 3 Influential factors of relative humidity in the vacuum chamber

t_d, t_w, and φ are the dry-bulb temperature, wet-bulb temperature and the relative humidity, respectively.

Results and discussion

The relative humidity was affected slightly by pressure p_A in the vacuum chamber (Fig. 4). During vacuum drying with chamber heating, the relative humidity decreased from 70% to 65% with p_A increased from 50 kPa to 101 kPa (Fig. 4). Therefore, moisture on the wood surface vaporized to some extent when the temperature of the wood rose due to thermal radiation from the heat source. During RF/V drying, dry-bulb temperature t_d did not change much but wet-bulb temperature t_w dropped sharply after radio frequency heating was stopped (Fig. 5). This phenomenon illustrated that leakage of electromagnetic waves occurred outside the electrode plates, resulting in the gauze wrapped on the wet-bulb thermometer to be heated by radiation. Therefore, it was not possible to precisely measure t_w during RF/V drying, but this was the correct value of t_w after radio frequency heating was stopped. Therefore, we calculated relative humidity by this value, t_d and p_A. In this experiment, the relative humidity φ was about 80%.

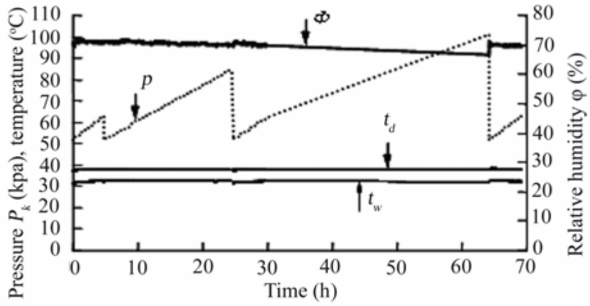

Fig. 4 Change of temperatures and relative humidity in the vacuum chamber during body heating.

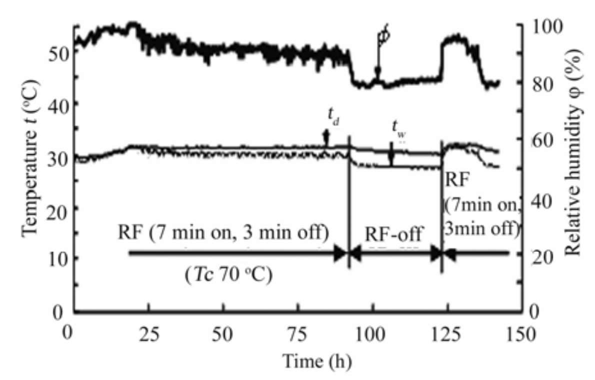

Fig. 5 Temperature and relative humidity in the vacuum during radio frequency/vacuum drying. t_d, and t_w: are dry-bulb temperature and wet-bulb temperarue in the vacuum chamber, respectively. Drying condition: regulate center temperature Tc 70°C, ambient pressure 24.5 kp.

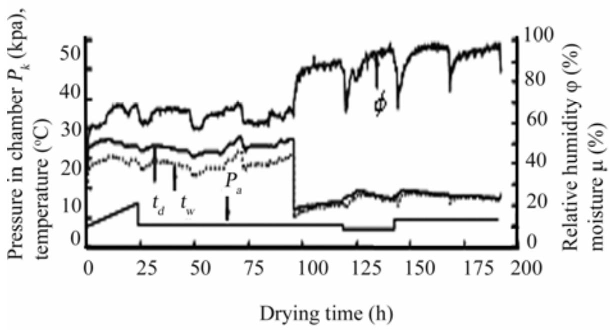

Fig. 6 Factors affecting relative humidity during vacuum drying. t_d, t_w, and φ are dry-bulb temperature, wet-bulb temperature in the vacuum chamber and relative humidity, respectively.

T_d and t_w played an important role in effect on the relative humidity φ, more specifically, φ decreased with the increase in the temperature (Fig. 6). This was probably because the saturated vapor pressure in the chamber increased with the rising temperature, while saturated vapor pressure in the condenser, which was almost equal to the partial vapor pressure in the chamber, remained unchanged. Here, further analysis was conducted based on the experiment. In this experiment, the temperature in the condenser was maintained at 32°C, correspondingly the partial vapor pressure in the chamber was about 4.8 kPa, whether the chamber was heated or not. When heating stopped, the temperature in the chamber dropped with a decline of the saturated vapor pressure, increase in φ, slowness of evaporation, and reduce of the condensation of vapor in the condenser. In the end, the condensation of vapor stopped when the temperature of the specimen was equal to the temperature of the saturated vapor in the condenser. At that point, the vapor pressure was equal to the saturated vapor pressure thus φ reached 100%, and evaporation from the specimen stopped. Even the temperature of the cooling water decreased, evaporation was instant because evaporation absorbed latent heat and the temperature of the wood surface decreased. As a result, without external heating, the temperature of the samples was always restricted by the temperature of the cooling water in the condenser. In this experiment, the maximum relative humidity was 97% due to leakage of the vacuum chamber. This indicated that there was no evaporation under the vacuum without external heating.

Conclusions

The relative humidity φ during vacuum drying is significantly affected by the temperature difference between the air in the vacuum chamber and the cooling water in the condenser. If the temperature of the cooling water is invariable, the partial vapor pressure in the chamber is also invariable. On the other hand, the saturated vapor pressure increases as the temperature in the vacuum chamber increases. As a result, the relative humidity φ decreases as the temperature in the vacuum chamber increases. Relative humidity during RF/V drying can be accurately measured after heating stops completely. The relative humidity was affected slightly by pressure p_A in the vacuum chamber. And the relative humidity decreased from 70% to 65% with p_A increased from 50 kPa to 101 kPa. There is no evaporation under the vacuum without external heating.

References

Cai YC, Hayashi K. 2001. Pressure and temperature distribution in wood during radio-frequency/vacuum drying. Tokyo: 7th International IUFRO Wood Drying Conference, 386−391.

Cai Y, Hayashi K. 2002. Contribution of evaporation from transverse section to drying rate during radio-frequency/vacuum drying. *Journal of the Japan Wood Research Society*, **48**(2): 73−79.

Cai YC, Hayashi K, Liu YX. 2003. Mechanism of moisture movement in wood during FR/V drying. Harbin: 9th International IUFRO Wood Drying Conference, 202−211.

Chen Zhangjing. 1997. Primary driving force in wood vacuum drying, Ph.D. Thesis, Virginia Polytechnic Institute and State University.

Chen Zhangjing, Lamb FM. 2001. Investigation of boiling front during vacuum drying of wood. *Wood and Fiber Science*, **33**(4): 639−647.

Chen Zhangjing, Lamb FM. 2004. A vacuum drying system for green hardwood parts. *Drying Technology*, **22**(3): 577−595.

Koumoutsakos A, Avramidis S, Hatzikiriakos SG. 2001. Radio frequency vacuum drying of wood: I. Mathematical model. *Drying Technology*, **19**(1): 65−84.

Koumoutsakos A, Avramidis S, Hatzikiriakos SG. 2001. Radio frequency vacuum drying of wood: II. Experimental model evaluation. *Drying Technology*, **19**(1): 85−98.

Li xianjun, Wu qingli, Jiang wei, Zhang biguang. 2006. Mechanism of moisture movement in wood during microwave vacuum drying. *Journal of Beijing Forestry University*, **28**(3): 150−153. (in Chinese)

Shin Terasawa. 1998. Wood radio frequency vacuum drying. Tokyo: Kaiseisha,p14.

Siau JF. 1995. Wood: influence of moisture on physical properties. Virginia: Department of wood science and wood products. Virginia Polytechnic Institute and state university, 39−63.

The Japan Society of Mechanical Engineers. 1959. Humidity-moisture measurement and Environment Monitoring. Otsu: Gihodo shuppansha, p43−51.